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INCREASING THE FORCE LIMITS OF THE MAGNETIC BALANCE SYSTEM

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FINAL REPORT

TR 199

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The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

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The report describes the construction and testing of new motor generator power supplies and filter inductors for use with the magnetic balance system. Motor generator output is ± 380 volts with a current limit of ± 300 amps and a power limit of 50 hp. Connected to the lift and drag circuits the supplies were tested up to 144 amperes in drag and 244 amperes in lift. Calculations of the performance of the 200 ampere 1.6 mh inductors as coupling

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(omega)(L/R)

networks are also presented as well as Q = $\omega L/R$ vs frequency measured for the coils. Measured Q at 20 KC was 660.

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PREFACE

This Final Technical Report covers work performed on Contract DAAG-29-76-C-0028 between April 15, 1976 and September 30, 1977 under the technical cognizance of Dr. Robert Singleton, Contract Monitor. The following scientific personnel have contributed to the effort:

Professor Eugene E Covert

Dr Charles W Haldeman

Mr Charles E Hawks

Mr Saghir Ahmad

Mr Benjamin Ziph

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INTRODUCTION

The magnetic balance system at the M.I.T. Aerophysics Laboratory has been used for the past several years to study the aerodynamics of many configurations of interest to the U.S. Army.

Recent research programs with this magnetic balance system have demonstrated its capability to support complex configurations (1) and accurately measure Magnus force on rotating bodies of revolution (2).

The angle of attack range of the balance system was recently increased under Contract DAAA21-74-C-0304 and the improved system was used to obtain aerodynamic data on a short, finned-body configuration (3). This increase in angle of attack range was achieved by incorporating prototype motor generator power supplies for the pitch and yaw degrees of freedom. These supplies increased the pitch angle capability for a body of L/D=4 from 10° to 38° wind off. However, the available lift and drag power supplies limited the angles for this body to about $\pm 20^{\circ}$ at 200 fps and $+15^{\circ}$ -5° at 400 fps. This power deficiency in lift and drag also limited the range of velocities and angles of attack covered in recent ring airfoil tests (4). Two isolating inductors in the pitch and yaw circuits are also overloaded by continuous operation at high angles of attack (3). Clearly, the need existed for further improvements in the power supplies and auxiliary equipment. This report describes the construction, installation and initial testing of two additional motor generator units and inductor units which have been installed to overcome the present limits.

Power Supplies

Two 50 hp motor generator units were constructed. Each consisted of four aircraft generators (Jack and Heintz Model G300-4BT) mounted to a steel baseplate and belt driven from a single Baldor 50 hp 1725 rpm electric motor (Catalog No. M2543-T). Each generator was provided with an independently movable ball bearing base to provide independent adjustment of belt tension and to absorb the radial load. Drive belts are 4-groove browning Poly-Vee size L. These were the largest size for which four belts could be fitted on the 20 groove sheave (maximum width available). Generator sheave diameter is 4 inches, which with the motor sheave diameter of 20 inches provides a drive ratio of 5:1 and a nominal generator speed of 8650 rpm. This is a slight reduction in speed and drive ratio from the prototype unit (3) for which the drive ratio is 8:1 and the generator speed is 9350 rpm. Since the prototype has operated over 700 hours to date without belt replacement, the current assembly appears conservative.

Initial operation of the assembled power supplies revealed a belt misalignment problem in one unit. The belts were replaced and the sheaves were carefully realigned. Approximately four hours of satisfactory operation has been completed since the alignment.

Field Driver Amplifiers

Four Torque Systems, Inc. PA-601 power amplifiers with power supplies and fans were mounted in a standard short relay rack. These amplifiers couple the magnetic balance electronics to the generator field windings. The circuit is shown in Figure 1 for one power supply. The other two channel supply is identical. A relay is provided between each power amplifier and the generator field, which is connected to the magnetic balance control circuitry. This prevents the generators from being energized if balance cooling water or generator cooling air is not present.

Main Power

440 volt power for the motor generators was run from the wind tunnel main 440 volt bus circuit breaker complex to the permanent generator location near the test section loading door. A photograph of the installation is shown in Figure 2.

Inductor Fabrication and Testing

The low current (50 amp) filter inductors in the pitch and yaw circuits were replaced to provide long term operating capabilities at 100 to 150 amps, the current obtainable from the prototype pitch and yaw supply (3). The new filter was designed to carry 200 amperes D.C. and to provide a low loss inductance at 20 kHz simultaneously. Twenty kHz is the EPS operating frequency. The new filters have been mounted from the ceiling above the magnetic balance area.

The new inductance coils are composed of 8 layers for a total of 87 turns of 3087 strand Number 36 Litz cable. Coil outside diameter is 16 inches, inside diameter 6.8 inches and axial length 4.4 inches. 3/8 inch wide by 1/4 inch thick axial spacers of G-10 fiberglass laminate are inserted every 2.5 to 3 inches along each layer to space the next layer, thus providing space for air cooling. After winding on an aluminum form the coils were vacuum impregnated with Emerson and Cuming Eccoseal 1207 epoxy resin using Catalyst 20. This served to cement the windings together and provide a smooth moistureproof and mechanically strong assembly. This resin system had sufficiently low viscosity that the air cooling passages drained free during cure. In order to provide flexible pigtails for connection, three (3) feet of cable at each end of the coil was covered with shrink tubing

and filled with silicone oil during epoxy impregnation. This maintained the flexibility of the wire pigtails. A comparison between design and measured parameters is shown in Table 1 below:

Table 1

COMPARISON OF DESIGN AND MEASURED COIL PROPERTIES

Design		Actual
Cable conductor	3100/36	3087/36 Nyleeze
diameter	.4 inch	.394 - .410
Turns	88	87
$Q = \omega L/R$ at 20 kHz	568	660
Inductance	1.32 mh	1.60 mh

The results of Q vs frequency measured on Both Coil 1 and Coil 2 are given in Figure 3. These values were measured from the bandwidth of a resonant circuit using mica transmitting capacitors. The results indicate that the coils should provide superior performance to the coils they are replacing.

Calculation of Performance of Inductance Coils for Coupling Roll Driving Power

The present magnetic balance circuit uses two separate filters in series to isolate the 20 kHz EPS signal and the 1.2 kHz roll drive power from the power amplifiers. These are shown in Figure 4. The new inductance coils will replace the second filter L_2 in this circuit. The first filter coil has adequate capacity for the present system needs. However, the D.C. power must flow through both coils.

A possibility for achieving improvement of performance exists by replacing the filter described above with a system of two inductively coupled RLC circuits, as shown in Figure 5. Now the D.C. current will pass only through the primary coil. This study was undertaken to provide a means of determining whether such a circuit was, in fact, advantageous.

The design of such an inductively coupled filter involves the selection of an appropriate combination of the seven circuit parameters; namely, R_1, R_2, L_1, L_2, C_1, C_2 and M, such that the frequency dependent impedance across the terminals A,B will have two magnitude peaks, sufficiently large, at the desired frequencies.

This circuit has the additional advantage that the roll driving power supply can be connected in series with R_2 without changing the circuit response as seen looking back into L_1.

Governing Equations

The magnitude of the impedance $|Z|$ across the terminals A,B (see Figure 4) as a function of the frequency ω, in terms of the seven circuit parameters, is given by the following expression:

$$|Z| = \frac{1}{\omega C_1}\left[\sqrt{1 + \frac{\frac{1}{\omega C_1}\left\{\frac{1}{\omega C_1} - 2\left[\omega L_1 + \frac{(\omega M)^2(\omega L_2 - 1/\omega C_2)}{R_2^2 + (\omega L_2 - 1/\omega C_2)^2}\right]\right\}}{\left[R_1 + \frac{(\omega M)^2 R_2}{R_2^2 + (\omega L_2 - 1/\omega C_2)^2}\right]^2 + \left[\omega L_1 - \frac{(\omega M)^2(\omega L_2 - 1/\omega C_2)}{R_2^2 + (\omega L_2 - 1/\omega C_2)^2}\right]^2}}\right]^{-1} \qquad (1)$$

Or, using the definitions:

$$k_m \equiv \frac{(\omega M)^2}{R_2^2 + (\omega L_2 - 1/\omega C_2)^2} \qquad (2)$$

$$A \equiv 1/\omega C_1 \qquad (3)$$

$$B \equiv R_1 + k_m R_2 \qquad (4)$$

$$C \equiv \omega L_1 - k_m\ (\omega L_2 - 1/\omega C_2) \qquad (5)$$

we have:

$$|Z| = A \left[1 + \frac{A(A-2C)}{B^2 + C^2}\right]^{-1/2} \qquad (6)$$

As is well known the ohmic resistance is frequency dependent in a monotonically increasing fashion. The frequency dependent resistance can be approximated by a three parameter, third order polynominal of the form:

$$R(\omega) = R_{DC} \quad \left(\frac{\omega}{\omega_b}\right)^2 \left(b-a\,\frac{\omega}{\omega_b}\right) + 1 \qquad (7)$$

where:

R_{DC} is the DC value of the resistance $R(0) \approx R_{DC}$

ω_b is the frequency for which $\dfrac{R(\omega_b)}{R_{DC}} = 2$

and is called the breakpoint frequency. It depends on the size wire used to make up the Litz cable.

From the definition of ω_b it is obvious that:

$$b-a = 1.$$

a and b can be regarded as constants:

$$b = 1.12,\ a = .12$$

Hence:

$$R(\omega) = R_{DC} \left(\frac{\omega}{\omega_b}\right)^2 \left(1.12 - 0.12 \frac{\omega}{\omega_b}\right) + 1 \qquad (8)$$

Equation 8 holds for $\frac{\omega}{\omega_b} \leq 7$.

Either Equation 6 or 1 describes a double-peaked curve like the one illustrated in Figure 6.

Because of the number of variables, Equation 6 was programmed on the IBM 370 at the MIT-IPC. For a prescribed set of circuit parameters, the program will search for the peaks of $|Z|\ (\omega)$ and yield as output the magnitude of the two peaks and the frequencies at which they occur.

This program was used with operator interaction in the time-sharing mode. By this means a cut and try design process could be completed very quickly. Several cases were computed and the values of tuning capacitance required were computed and tabulated using as inputs the properties L_1, R_1, ω_b measured for the new inductors. The results are listed in Tables 2 and 3. These indicate that the new coils will also be usable in the circuit of Figure 5 if it becomes advisable and the necessary design parameters have been determined.

Performance Measurements

D.C. performance tests were made by operating the new supplies both unloaded and loaded by the drag or lift magnetic balance coils. Excitation was obtained from a battery connected to a potentiometer.

The results of these tests are given in Tables 4 and 5. These indicate that the D.C. output of the supplies is considerably higher than was anticipated.* After operating at the maximum output listed in Table 4, 429 volts, indications of overheating of the interpole winding pigtails was found. It is thus planned to operate below 380 volts output. This level is 58 percent above the anticipated maximum level of 240 volts.

*Maximum output voltage was nearly twice what was expected from earlier D.C. output tests on one generator alone. The early measurements were in error.

$R_1 = 5.4 \times 10^{-2}\,\Omega$

$L_1 = 1.6 \times 10^{-3}\,H$

$\omega_b = 5 \times 10^4$ rad/sec

	$R_2\Omega$	C_1(F)	C_2(F)	M (H)	f_1 (kHz)	$\|Z\|_1$ (kΩ)	f_2 (kHz)	$\|Z\|_2$ (kΩ)
Case 1 $L_2=1.6\times10^{-2}\,H$	1A $R_2=5.4\times10^{-1}\,\Omega$	6×10^{-8}	10^{-6}	3.2×10^{-3}	1.256	1.148	20.985	31.621
	1B $R_2=5.4\times10^{-2}\,\Omega$	6×10^{-8}	10^{-6}	3.2×10^{-3}	1.256	6.118	20.977	38.924
Case 2 $L_2=1.6\times10^{-3}\,H$	2A $R_2=5.4\times10^{-2}\,\Omega$	6×10^{-8}	10^{-5}	9.45×10^{-4}	1.256	1.011	20.137	36.705
	2B $R_2=5.4\times10^{-2}\,\Omega$	6×10^{-8}	3.5×10^{-6}	1.05×10^{-3}	2.1	3.1	21.6	26.6
Case 3 $L_2=1.6\times10^{-4}\,H$	3A $R_2=5.4\times10^{-3}\,\Omega$	6×10^{-8}	10^{-4}	3×10^{-4}	1.256	1.018	20.187	36.871
	3B $R_2=5.4\times10^{-3}\,\Omega$	7×10^{-8}	3.8×10^{-5}	3.3×10^{-4}	2.0	3.2	19.9	25.8

Table 2

RESULTS FOR THE MAGNETIC BALANCE FILTER DESIGN
Cases 1-3

$R_1 = 5.4 \times 10^{-2}\,\Omega$, $\omega_b = 5 \times 10^4$ rad/sec

$L_1 = 1.6 \times 10^{-3}\,H$

$L_2 = 10^{-1}\,H$

$R_2 = 5 \times 10^{-1}\,\Omega$

M (H)	C_1 (F)	C_2 (F)	f_1 (kHz)	$\|Z\|_1$ (kΩ)	f_2 (kHz)	$\|Z\|_2$ (kΩ)
8×10^{-3}	6×10^{-8}	2×10^{-7}	1.123	5.83	20.974	39.38
7×10^{-3}	6×10^{-8}	1.6×10^{-7}	1.256	5.88	19.506	49.81
6×10^{-3}	5×10^{-8}	1.6×10^{-7}	1.256	3.32	20.216	67.97
5.8×10^{-3}	5×10^{-8}	1.7×10^{-7}	1.219	3.78	20.019	62.09
5.7×10^{-3}	5×10^{-8}	1.7×10^{-7}	1.219	3.69	19.929	67.83

Table 3

RESULTS FOR THE MAGNETIC BALANCE FILTER DESIGN
Case 4

Table 4

MEASURED PERFORMANCE OF GENERATOR UNIT 2 (DRAG)

Input to Amplifier Millivolts	Generator Field Excitation Volts	Coil Current Amperes	Armature Output Volts
0	0	0 (open)	1.70
25	.75	0	49.8
50.1	1.75	0	89.7
75.1	2.7	0	142
100	3.7	0	191
125	4.65	0	236
150	5.6	0	288
175	6.6	0	315
201	7.6	0	343
225	8.6	0	366
250	9.6	0	384
275	10.6	0	398
300	11.6	0	410
350	13.6	0	430*
101	3.8	0	192
0	0	3.2 (connected)	6
25	.7	21.2	39
50.2	1.8	44.8	81.5
75.1	2.8	68	125
101	3.8	88.8	165
125	4.8	105.6	195
150	5.8	119.2	225
175	6.8	129	246
200	7.8	138	265
225	8.8	144	279

*Interpole windings overheated.

Table 5

MEASURED PERFORMANCE OF GENERATOR UNIT 1 (LIFT)

Input to Amplifier Millivolts	Generator Field Excitation Volts	Coil Current Amperes	Armature Output Volts
0	1*	12.2	11
100	4.75	178	160
125	5.9	200	182
151	7.2	221	200
175	9.0	233	212
200	9.4	244	222

*Apparent D.C. offset in driving amplifier.

Comparison with Pitch-Yaw Supply

In order to compare the performance of the G300-4BT with the G.E. 2CM73B7 model generators currently in use on the pitch and yaw supply, one of the latter generators was replaced by a new unit and frequency response measurements were made. The circuit for frequency response tests is shown in Figure 7 and the resulting time constant as a function of amplifier driving voltage is shown in Figure 8. These tests indicated that the time responses were designed so the G300-4BT generators were used.

Impact on System Performance

Initial tests of the new motor generator power supplies indicate that the improvement in the force capability of the magnetic balance is greater than was anticipated. Use of these supplies should about triple the accessible angle of attack range at $q \approx 1$ psi and should double the accessible q at angles below 10 degrees.

The design currents for the new supplies are listed in Table 6 below along with the measured maximum values.

Table 6

MAGNETIC BALANCE CURRENT LIMITS

Status	Original Thyratron Supplies	Design Values for New Motor Generators in Lift Drag Pitch and Yaw using New Inductors	Achieved in Test
Degree of freedom			
Pitch-Yaw	±50	±150	
Lift	±50	±200	222
Side Force	±25	±50	
Drag	+40 - 10	±100	144

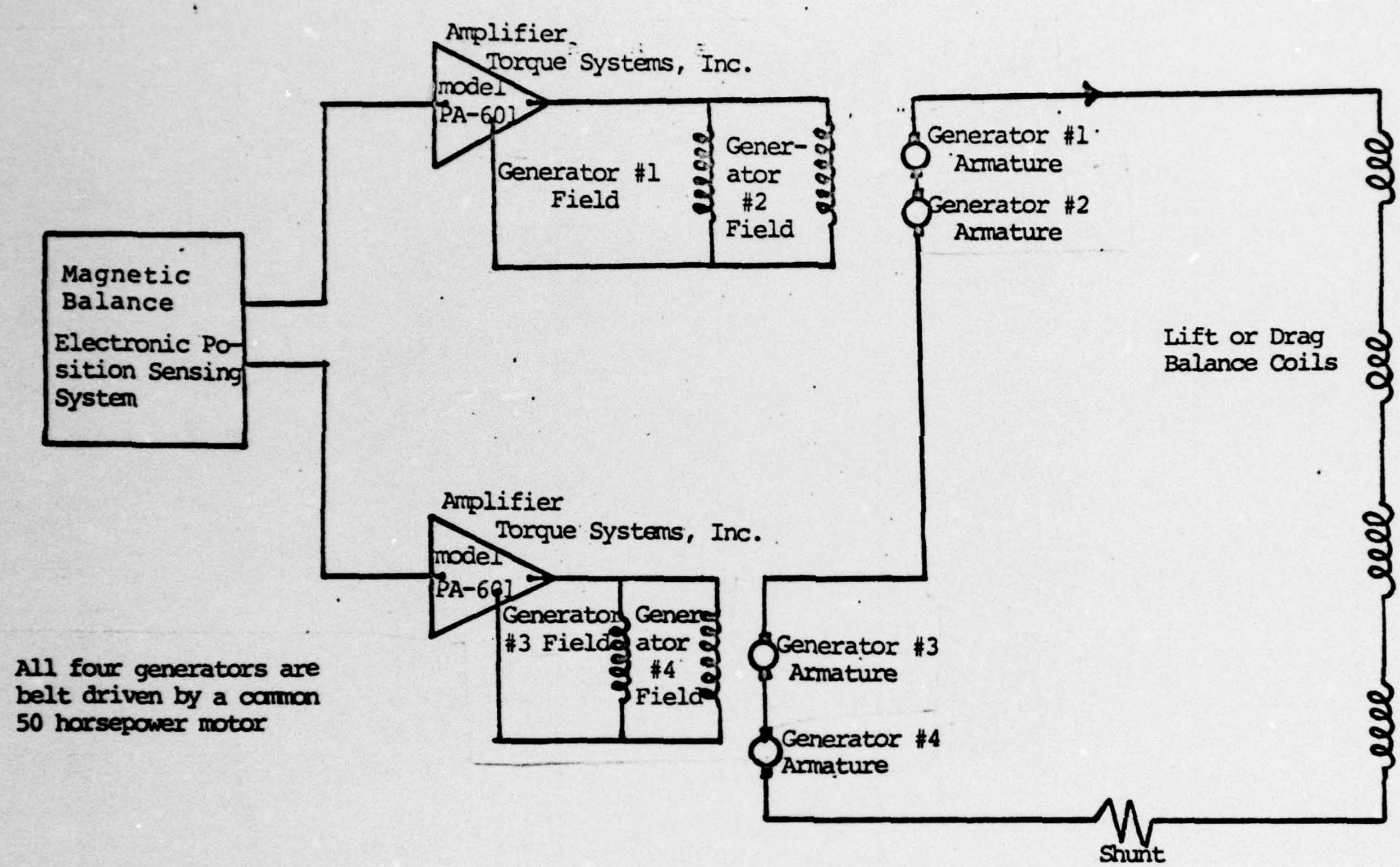

Figure 1. Block Diagram of Power Supply Typical of Both Units - Drive Motor not shown

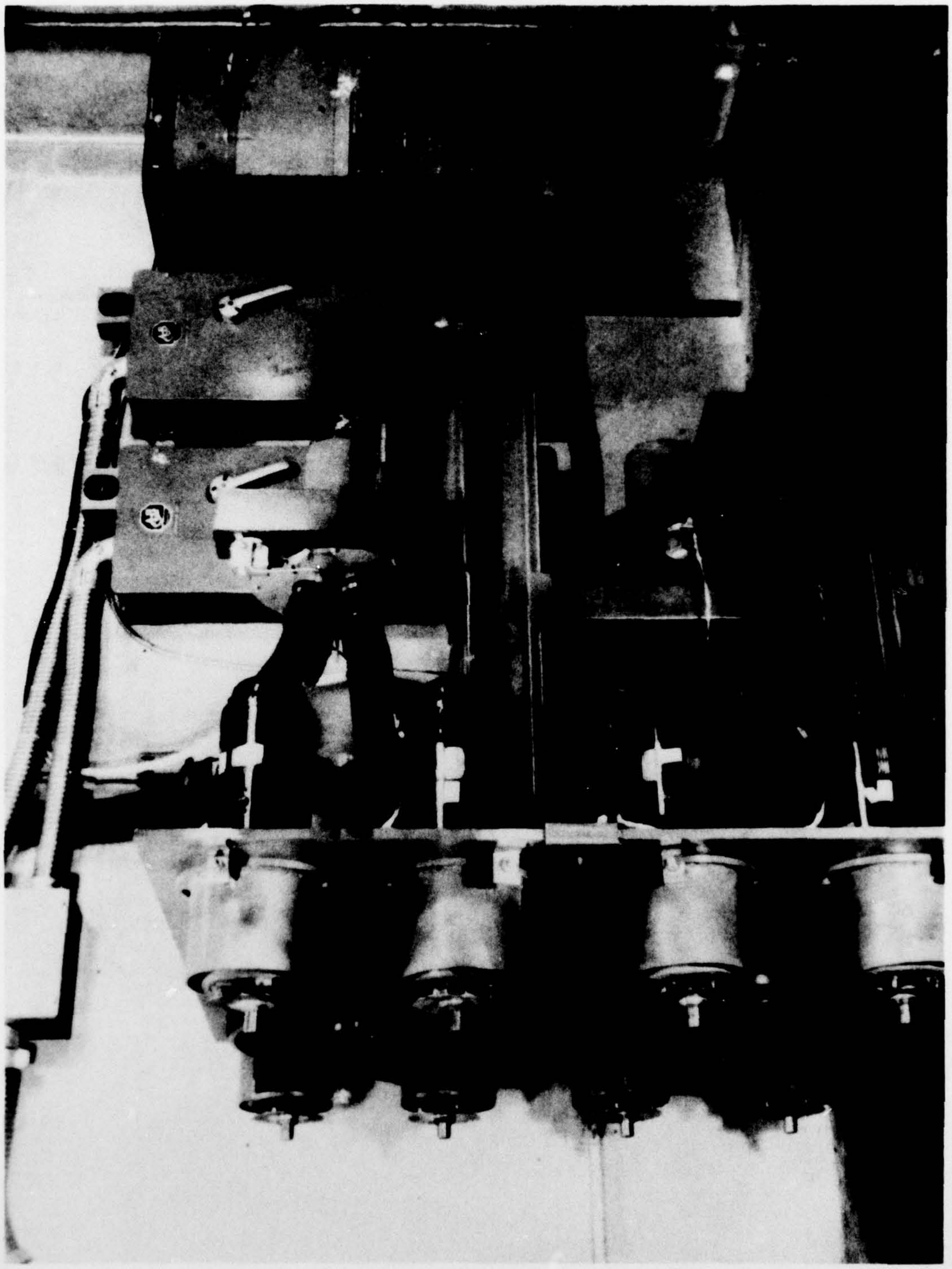

Figure 2. New Power Supplies for Lift and Drag Degrees of Freedom

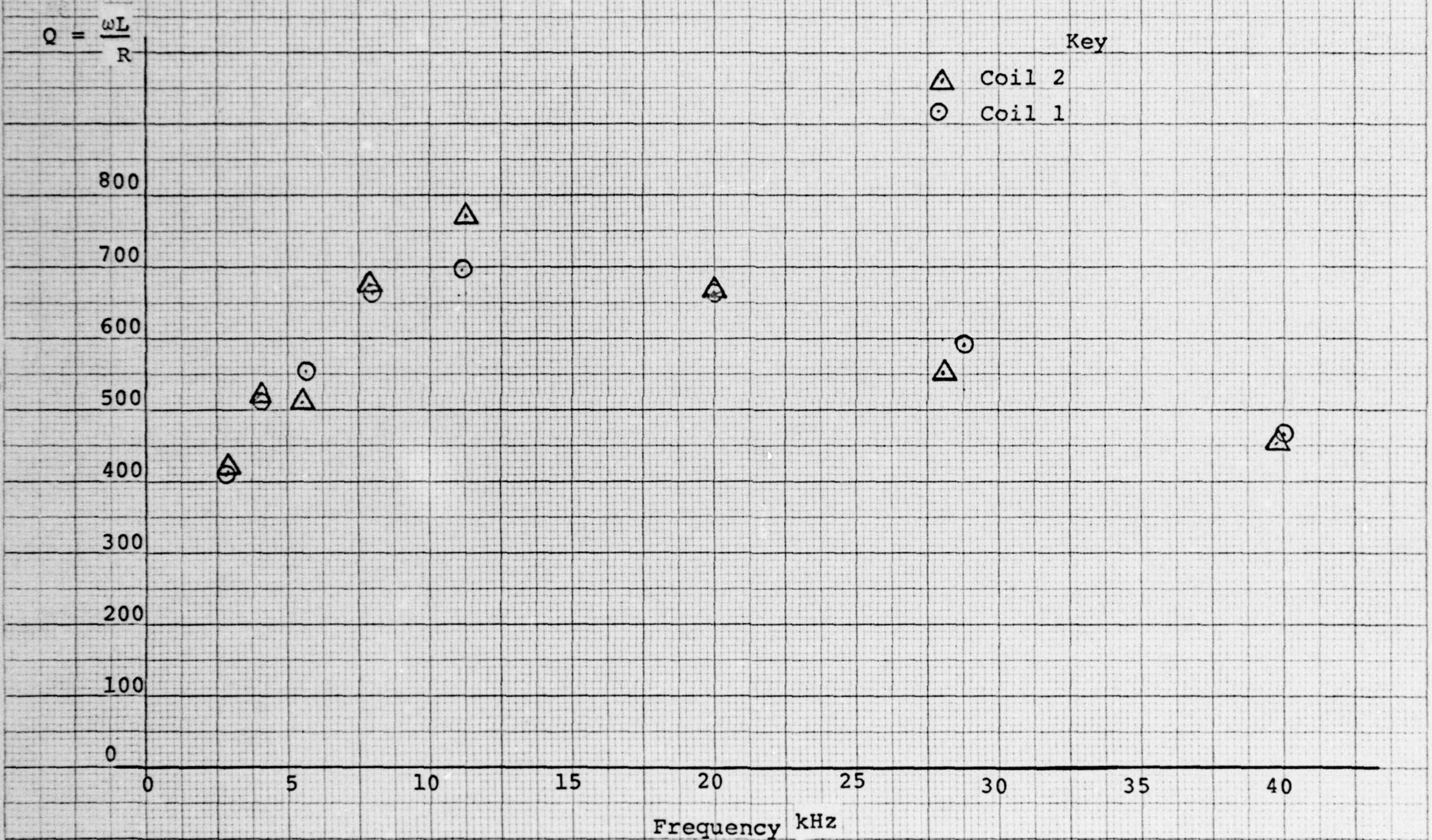

Figure 3. Q vs. Frequency for Inductance Coils

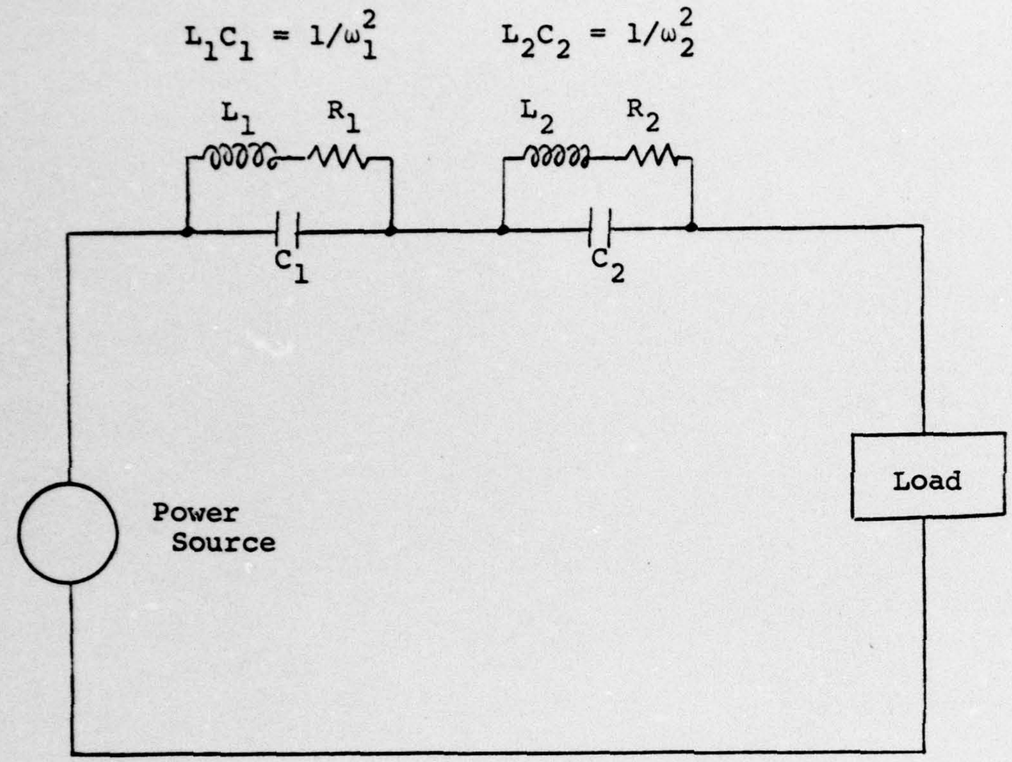

Figure 4. Two-Band Pass Filters in Series

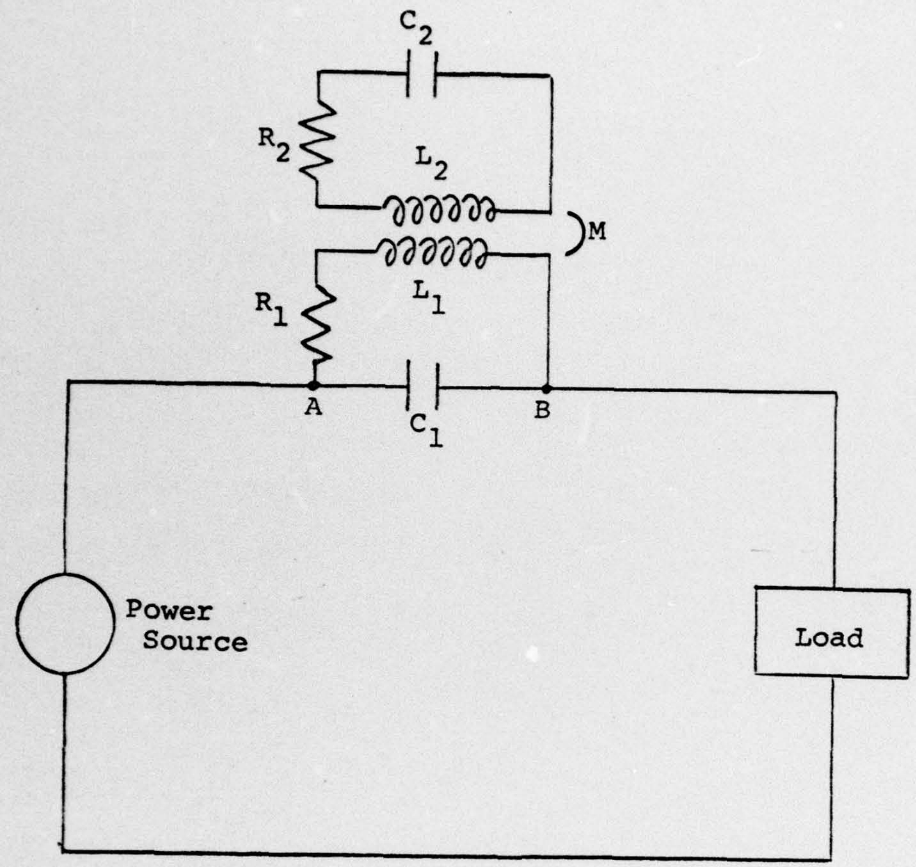

Figure 5. Inductively Coupled Filter

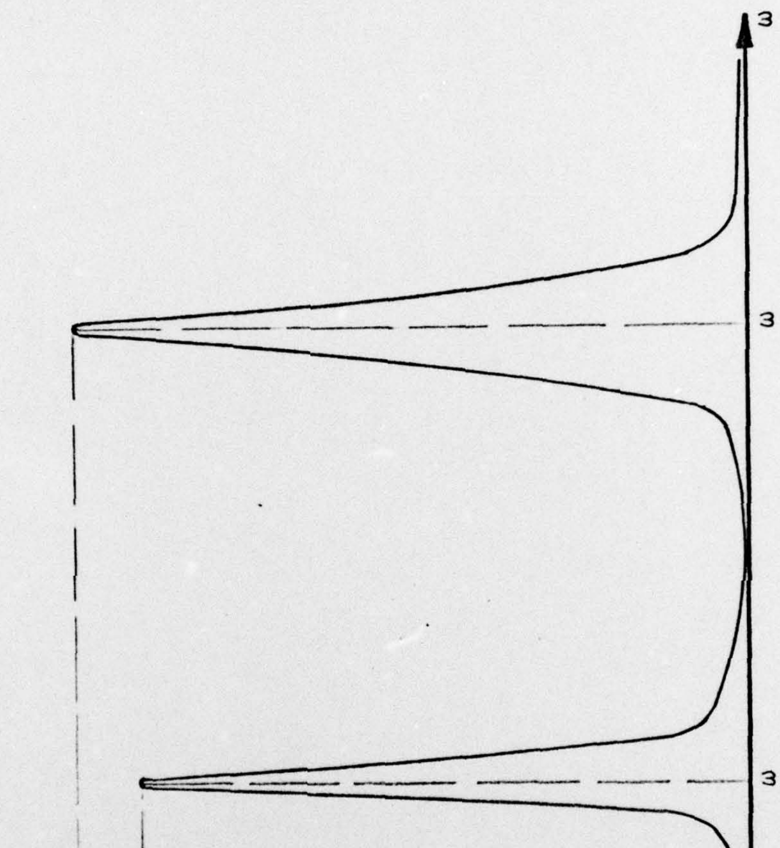

Figure 6. Impedance Curve

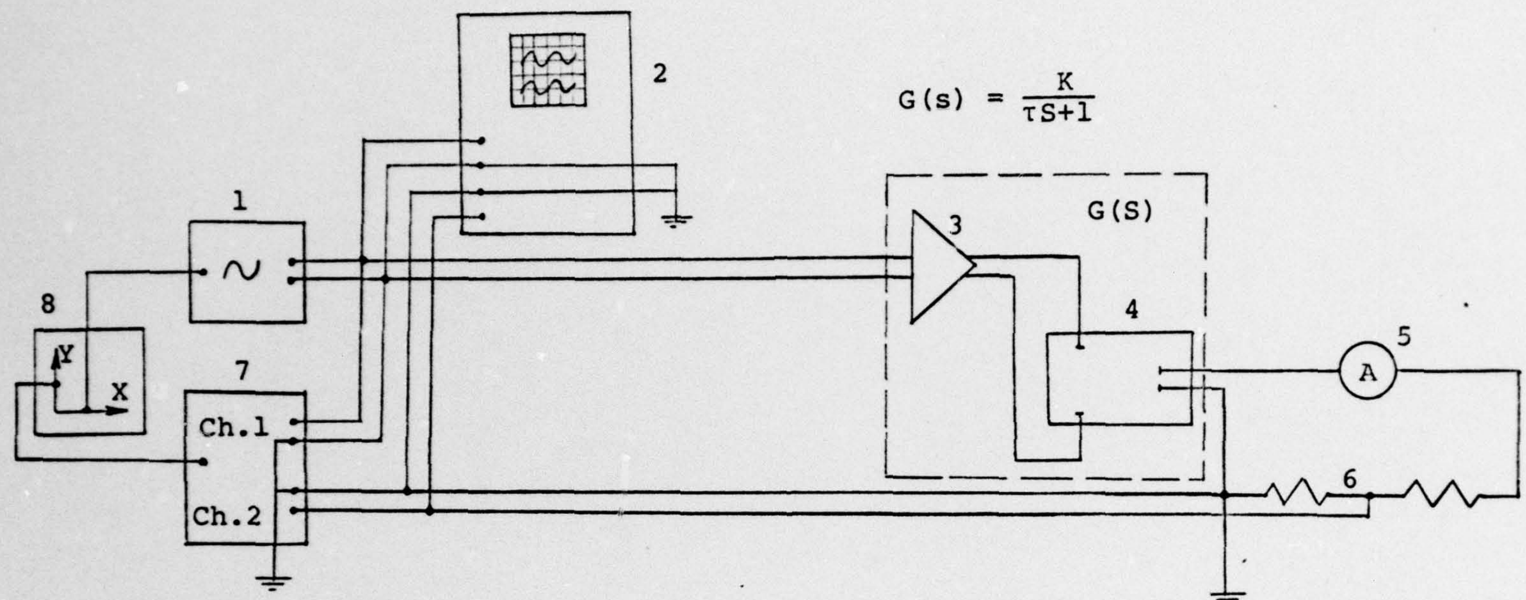

Figure 7. Block Diagram of Frequency Response Test Apparatus

1. Sweep Oscillator. 2. Dual Beam Oscilloscope.
3. Power Amplifier. 4. Generator. 5. Ammeter.
6. Voltage Divider. 7. Wave Analyzer. 8. X-Y Plotter.

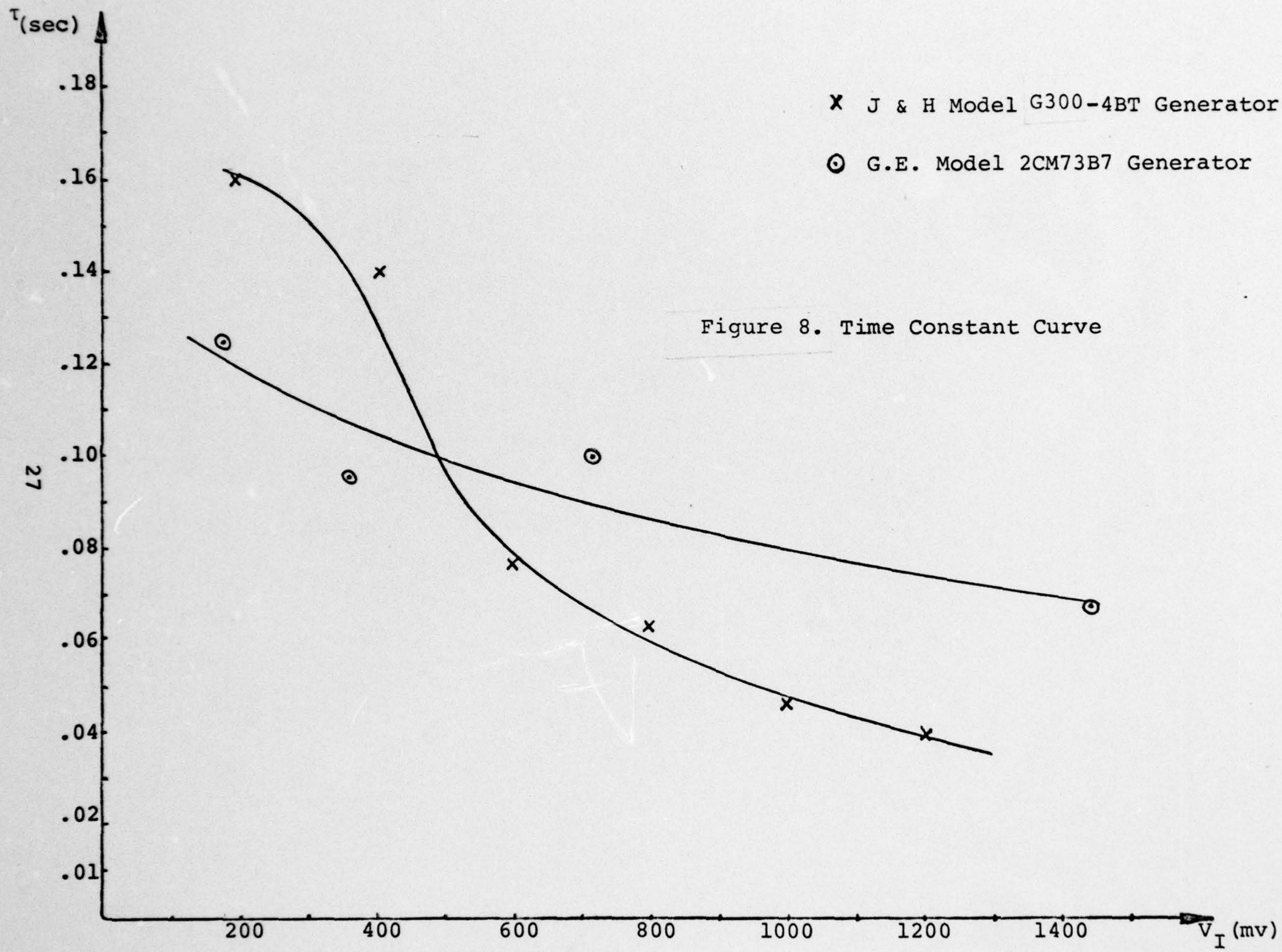

Figure 8. Time Constant Curve

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